ARMY RESEARCH LABORATORY

Analytical ^{60}Co Dose-Rate Contour Maps

by George A. Huttlin

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Analytical ^{60}Co Dose-Rate Contour Maps

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Abstract

A computer program is available for calculating dose-rate distributions for a variety of source configurations commonly used at the Army Research Laboratory Cobalt-60 Facility at Adelphi, MD. The underlying physics and mathematics are presented to document the program and to provide the necessary background for technicians serving as facility operators and other potential users of the program. Instructions for using the program are included.

Contents

Figures

Table

1. Introduction

It is possible, at least in principle, to calculate exactly the dose and dose rate at any position relative to any configuration of radioactive sources of known gamma (γ) activities, provided that scattering in transit between the source and target can be neglected.

A computer program is available for calculating dose-rate distributions for a variety of source configurations commonly used at the Cobalt-60 Facility at the Army Research Laboratory (ARL) Adelphi site. In the present version, the program also neglects attenuation. This assumes that the containers are sufficiently thin that air does not attenuate the radiation (not a bad assumption for short distances), and that there is no water surrounding the rods. For the circular configurations used in the pool, this latter assumption is not completely justified inside the exposure can, since the radiation has to pass through some water and the can itself to get there. Nevertheless, the assumption is good enough inside the can for our purposes.

This type of analytic calculation is not possible with precision for flash x-ray machines because of their inherent shot-to-shot irreproducibility and because of the intricacies of the interaction of the electrons with the x-ray–producing target. However, with sources such as ^{60}Co, the radiation is very simply described. Although at the nuclear level the decay is a complicated statistical process, the repeatability of experiments and the simplicity of the description are assured by the very large number of ^{60}Co nuclei ($\sim 10^{23}$) and the large decay rate ($\sim 5 \times 10^{14}$ decays per second for the elevator source). The only thing irreproducible in practice is the transition as the source and object to be irradiated are brought together.

The ^{60}Co in Building 504 at the Adelphi site is contained inside $\frac{9}{16}$-in.-diameter, 13-in.-long, stainless-steel cylinders. The ^{60}Co itself is a 12.5-in.-long nonuniform helix with sufficient windings to be approximated by a cylinder. For this calculation, however, I assume that the ^{60}Co has a uniform linear distribution. (A more complicated calculation could be done assuming a cylindrical distribution. However, at the distances of interest, the assumption of uniformity has a more significant effect.)

2. Point Source

I begin with a point source having no extent and occupying an ideal, single position in space. Imagine the source point to be at the center of imaginary spherical shells of different radii r. At any instant in time, the total amount of radiation passing through a shell of radius r_1 must equal the total radiation passing through a shell at any other radius r, as long as the radiation is not attenuated.* The total amount of radiation is proportional to the activity A of the source. The dose rate $\dot{D}$ at any distance r is proportional to the amount of radiation passing through an area (such as a square centimeter, square inch, or square meter) at that distance. The radiation per area at the distance r, then, is the total amount of radiation divided by $4\pi r^2$, which is the area of the sphere at r. Putting this together, we have

$$\dot{D} = \frac{Af}{4\pi r^2} \,, \tag{1}$$

where the proportionalities are contained in the factor f.

This factor f holds all the information on the type of radioactive material and on the material ultimately absorbing the radiation (that is, the material of interest in the irradiation). Since it is known[1] that a point source of ^{60}Co with a 1-Ci activity† produces a dose rate of 1.35 roentgens/hr at a distance of 1 m, f is seen to have the value $4\pi \times 1.35$ roentgens$\cdot$hr$^{-1}\cdot$Ci^{-1}.

* I am also assuming that the rate at which radiation is emitted changes slowly over the time it takes the radiation to travel from the point source to the outermost of the spheres of interest.

1 Robley D. Evans, *The Atomic Nucleus*, McGraw Hill Book Company, New York, 1955, p. 723.

† "Ci" is the abbreviation for the "curie," the unit of radioactivity corresponding to 37 giga-becquerels (gBq) or 37 billion disintegrations per second.

3. Line Source

To extend this calculation to a distributed source as shown in figure 1, I write equation (1) in differential form:

$$d\dot{D} = \frac{f}{4\pi r^2} dA \ . \tag{2}$$

If the source is a line source of total activity A and length L, dA can be replaced by

$$dA = \frac{A}{L} dl \ , \tag{3}$$

where dl is the differential measurement of length l along the line source. Although not explicitly stated in equation (2), r is a function of l. As shown in figure 1, let the line source lie on the z-axis of a system of cylindrical coordinates with its center in the ρ-ϕ plane. For convenience, let $l = 0$ at the center of the source. The coordinates ρ, ϕ, and z give the position of the arbitrary field point with respect to the line source. Now, the distance r from the differential source element to the field point can be written in terms of l, ρ, and z:

$$r^2 = (z - l)^2 + \rho^2 = (l - z)^2 + \rho^2 \ ; \tag{4}$$

and equation (2) becomes

$$d\dot{D} = \frac{fA}{4\pi L[(l - z)^2 + \rho^2]} dl \ . \tag{5}$$

To obtain the net dose rate from the line source for any position (ρ, ϕ, z), we integrate equation (5) over l:

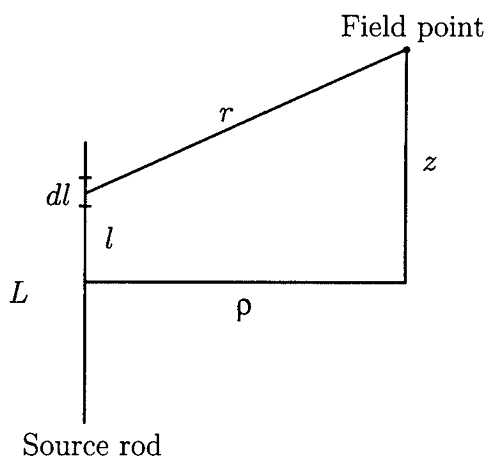

Figure 1. Geometry for calculation of dose rate at arbitrary field point from line source (source centered at $z = 0$).

$$\dot{D} = \frac{fA}{4\pi L} \int_{-L/2}^{L/2} \frac{dl}{(l-z)^2 + \rho^2} \ . \tag{6}$$

Since z is a constant in the integration, $d(l-z)$ can be substituted for dl. We can then simplify things by substituting $\zeta = l - z$. Equation (6) then has the appearance

$$\dot{D} = \frac{fA}{4\pi L} \int_{l=-L/2}^{l=L/2} \frac{d\zeta}{\zeta^2 + \rho^2} \ , \tag{7}$$

which has the solution

$$\dot{D} = \frac{fA}{4\pi \rho L} \arctan \frac{\zeta}{\rho} \bigg|_{l=-L/2}^{l=L/2} \tag{8}$$

for $\rho \neq 0$. Replacing ζ with the original variables, plugging in the limits, and maneuvering the minus sign gives the result

$$\dot{D} = \frac{fA}{4\pi \rho L} \left(\arctan \frac{\frac{1}{2}L + z}{\rho} + \arctan \frac{\frac{1}{2}L - z}{\rho} \right) \ . \tag{9}$$

If $\rho = 0$ and $|z| > L/2$, which is to say for positions along the line defined by the wire but not on the wire, the integral (7) gives the result

$$\dot{D} = \frac{fA}{\pi(4z^2 - L^2)} \ . \tag{9a}$$

4. Arrays of Source Rods

The ^{60}Co rods in Building 504 are arranged in two different geometries: planar and circular. At the field point, the dose rate is simply the sum of the dose rates from the individual source rods:

$$\dot{D} = \frac{fA}{4\pi L} \sum_{n=1}^{N} \frac{1}{\rho_n} \left(\arctan \frac{\frac{1}{2}L + z}{\rho_n} + \arctan \frac{\frac{1}{2}L - z}{\rho_n} \right) . \tag{10}$$

I am assuming that the rods are all parallel to the z-axis, have the same length, and are all centered at $z = 0$. Therefore, the variation from rod to rod is in ρ_n and not in z.

The *elevator* source is an array of parallel source rods in a plane with a uniform separation s, as shown in figure 2. To sum the dose rates from the individual rods, it is convenient to switch from cylindrical to Cartesian coordinates. Let the x-y plane be the same as the ρ-ϕ plane, with the x-axis perpendicular to the plane of the rods and the z-axis parallel to the rods, as before. The y-axis then is perpendicular to each of the rods, but lies in the source plane. The origin is in the source plane at the center of the rod array.

In the substitution $\sqrt{x_n^2 + y_n^2}$ for ρ_n, x_n has the constant value x from rod to rod. However, the value y_n varies and is given by

$$y_n = y + \frac{1}{2} s(N + 1 - 2n) , \tag{11}$$

where y is the position of the field point relative to the center of the array, s is the center-to-center separation of adjacent rods in the array, N is the total number of rods in the array, and n is the summation index.

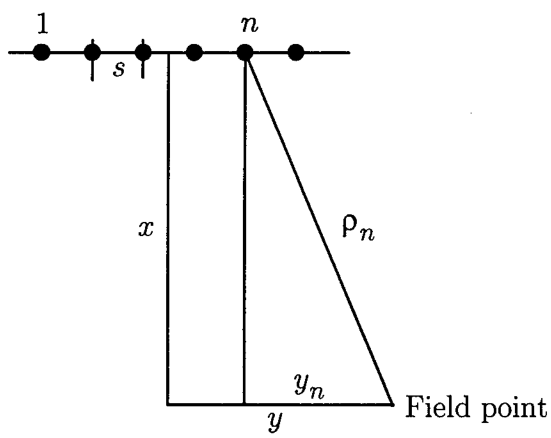

Figure 2. Geometry for calculation of dose rate at an arbitrary field point from a planar distribution of parallel line sources, all centered at $z = 0$.

The rods in the H_2O pool are arranged in parallel in circular arrays with a uniform rod-to-rod spacing, as shown in figure 3. It is convenient in this situation to place the origin at the center of the source array, with the z-axis being the axis of the array. Now ρ_n in equation (10) is replaced by

$$\rho_n = \sqrt{(R\cos\theta_n - x)^2 + (R\sin\theta_n - y)^2}\ , \tag{12}$$

where $\theta_n = 2\pi n/N$ and R is the radius of the array.

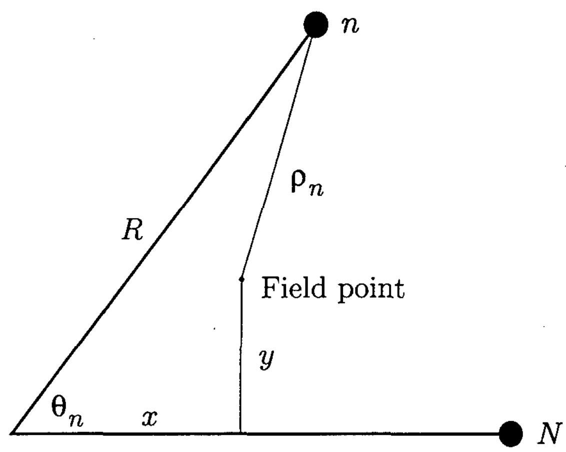

Figure 3. Geometry for calculation of dose rate at an arbitrary field point from a circular array of parallel line sources, all centered at $z = 0$.

5. The Program

The mathematics above is embodied in the C program DEAVER, named for Jim Deaver who operated the ^{60}Co facility in 1993, when I worked out the mathematics, wrote the first version of the program in FORTRAN, and ran it using the graphics package DISSPLA on a VAX-4200. The present program runs on PCs and uses the graphics package GraphiC.

5.1 Calibration Data

DEAVER contains information about the activity of each of three different "types" of ^{60}Co rod. These are traditionally known as the "A," the "B," and the "elevator" sources. These types are identical, except for activity. The activity at any given time is, of course, affected by the exponential decay of the ^{60}Co, which has a 5.271($\pm$0.001)-year half-life.[2] This means that the time dependence of the ^{60}Co activity is given by

$$A(t) = A(t_0)2^{-(t-t_0)/\tau_{1/2}} \ , \tag{13}$$

where A is the activity, t is the time of interest, t_0 is some reference time, and $\tau_{1/2}$ is the half-life.

The activities used in the program make use of the reference data shown in table 1.

The program displays dose rates in units of rads per unit time in silicon; however, in the equations thus far, the constant f gives results in roentgens. To convert from roentgens to rads in air, multiply the result by 0.869 rads(air)$\cdot$roentgen^{-1}. Then to convert from rads(air) to rads(Si), multiply the result by 0.9962. The conversion from rads(Si) to rads(H_2O) requires multiplication by 1.1102.*

Table 1. Activity Reference Data

Source	Net activity (Ci)	Reference date m/d/y	Number of source rods
Source A	32862	7/1/1975	24
Source B	2219	7/1/1975	8
Elevator (C)	34730	12/1/1986	8

[2] Jagdish K. Tuli, *Nuclear Wallet Cards,* National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York, January 1985, p. 8.

* Klaus G. Kerris, private communication.

5.2 Operation of the Program

1. Type `DEAVER` $\Downarrow$ (Note that `typewriter type` indicates input; the arrow $\Downarrow$ indicates the return key.)
2. Follow the prompts. First enter the date of interest. This is done in the order month $\Downarrow$, day $\Downarrow$, year $\Downarrow$. Use a number for the month, and use four digits for the year. (The year 2000 is fast approaching, and I did not want to confuse the program with the extra logic needed for the new millenium with only two-digit years.)
3. Identify the rods with one of `1` $\Downarrow$, `2` $\Downarrow$, or `3` $\Downarrow$, for rods from the sources A, B, or C (elevator), respectively. If you enter anything the computer does not like, it will simply repeat the question. (This does not imply that the computer will protect you from all errors.) You may use the elevator rods in a circular array or rods from either source A or source B in a planar array, if you would like.
4. Enter the number of rods. The values in brackets `[ ]` at the end of some inquiries indicate the default values that will be used if you enter `0` $\Downarrow$. The default values, in some cases, are the *only* sensible values. For instance, there are only eight rods of the elevator type. However, since having 1745 rods breaks no laws of physics, the program will accept such entries.
5. Enter the length of each rod. All the rods are 12.5 in. long. Nevertheless, any length is accepted. Just remember that all lengths in the program are in inches.
6. Next, you will be shown a list of options. All the plots are contour plots. The program works with two different configurations of rod arrays, planar and circular, as described in the theory section. Contour plots for the planar array are available in any of three planes: option 1 gives a contour plot in any plane described by constant z, option 2 applies to constant x, and option 3 applies to constant y. For normal usage of the elevator sources, I would advise running the program twice: once with option 1 and then, after seeing what position x looks interesting, once with option 2 for that value of x. The circular configuration can be viewed in the constant-z plane, option 4, or in a vertical plane formed by the z-axis and the radial line at $\phi = 0$ (option 5). Option 6 permits you to calculate numerical dose rates for any number of points (x, y, z) for the planar configuration.
7. About the array...
   - 7a. If you choose one of the options for the planar configuration, you will be asked for the center-to-center spacing of adjacent rods.
   - 7b. If you choose the circular configuration, you will be asked for the diameter of the circle of rods. The program assumes that the rods are uniformly spaced over the entire circle.

8. Offsets...
   8a. Next, you are asked about an "offset" value. The offset has a different meaning for each of the options. The offset is the value of z, for instance, for the contour plot in the (x, y) (z = constant) plane, etc. If the contour plot is to be in the (y, z) plane, then the offset value is the value of x. Note that in all cases, the rods lie along the z-axis and have their centers at $z = 0$. The options for the planar array have the rods lined up along $x = 0$. So, for a plot in the (y, z) plane at $x = 5$ in., use option 2 with an offset value of 5.
   8b. Normally, one of the rods in the circular configuration is at $\phi = 0$. If you choose option 5, you can introduce an angle by which to offset the circle of sources, so that the plot will effectively show, for instance, what is happening between the pencils.
9. If you choose one of the three options for the planar array, you will be asked for the "distance at the far right of the screen." This value is no more than the magnification of the plot. For options 1 and 3, the rods at $x = 0$ will be shown at the far left of the plot, and the value you enter will determine the value of x at the right of the plot. For option 2, the center of the rod array (the x-axis) will be in the center of the plot, and the value you enter will determine y at the right and left of the plot. To force the plotting routines to use reasonable values for labeling the axes, the program makes the plot a little more extensive than the value you enter.
10. The plot will now be displayed on the screen. Once you have finished viewing it, you can either...
    10a. return to DOS by typing $\Downarrow$
    10b. get a printout of the plot by hitting the escape key. Shift L will then generate the printed plot. This will take a while. Hit return or escape when the printer is finished, and follow the instructions on the screen.

6. Results

Output plots from sample calculations are shown in figures 4 to 7. All these were calculated for the reference date January 1, 1996. You can use the equi-dose-rate contours in these plots for other dates without running the program again by replacing activities $A(t)$ and $A(t_0)$ in equation (13) with the dose rates $\dot{D}(t)$ and $\dot{D}(t_0)$, respectively. $\dot{D}(t)$ is the dose rate on a particular contour for the date of interest, and $\dot{D}(t_0)$ is the dose rate on January 1, 1996, shown in the plot. The time interval $t - t_0$ is the interval from the date of interest back to the reference date. For dates before the reference date, $t - t_0$ is a negative quantity. For instance, for January 1, 1998, the factor $2^{-(t-t_0)/\tau_{1/2}}$ is evaluated $2^{-2/5.271} = 0.769$, so that the $10^2 = 100$ rads(Si)/s contour on a January 1, 1996, plot will represent 76.9 rads(Si)/s on January 1, 1998.

Figure 4 applies to all eight elevator rods spaced at the normal 1.25 in. apart in the plane intersecting the middle of the rods (offset = 0) and parallel to the floor. The contours are spaced linearly through each of the logarithmically spaced decades and are labeled only at the decade positions. The contours to the right of the $10^1 = 10$ rads/s are, in order, 9 and 8 rads/s, etc., while the contours going to the left from 10 rads/s are 20, 30, 40, etc. up to 100, beyond which the contours are for 200, 300, 400, etc., rads/s.

Figure 5 represents the same setup as for figure 4 but gives the contours in the plane 5 in. (offset value) in front of the rods. Because the dose rates over slices of space parallel to the plane of the rods are more uniform, the contours are labeled linearly.

Figure 6 shows the eight elevator rods in a 5-in.-diameter circular array in the pool. The contour map is for the plane that bisects the rods (offset = 0). The contours have linear spacing. The program will generate contours for any number of rods and will assume that they are equally spaced over the entire circle. However, since there are 24 holes at the 5-in. diameter in the rod-support fixture, in reality only 1, 2, 3, 4, 6, 8, 12, and 24 rods can be spaced uniformly. The present version of the program does not handle nonuniform spacings, nor does it handle rods of different activities in the same calculation. To get around that, one should generate separate plots for uniform distributions, then overlay the plots, and add the results manually. To get data for 23 rods (using the 24-hole circle), do the calculation for 24 rods, then for one rod, and subtract the results. Note that only dose rates shown inside the circle of rods (and therefore inside the water-tight exposure cylinder) can be trusted. The water outside the can attenuates ^{60}Co gamma radiation by a factor of 2 every 4.2 in. or so. This attenuation is not considered in the calculation.

Figure 7 is the axial view of the source configuration in figure 6.

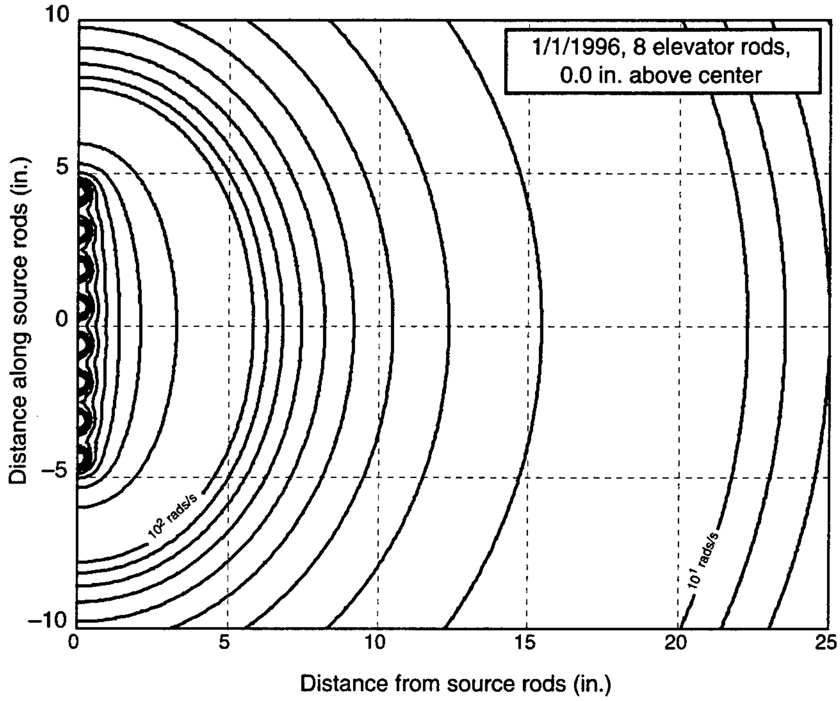

Figure 4. Sample result for a planar array of all eight high-intensity source rods, showing dose-rate contours in plane bisecting rods and parallel to floor.

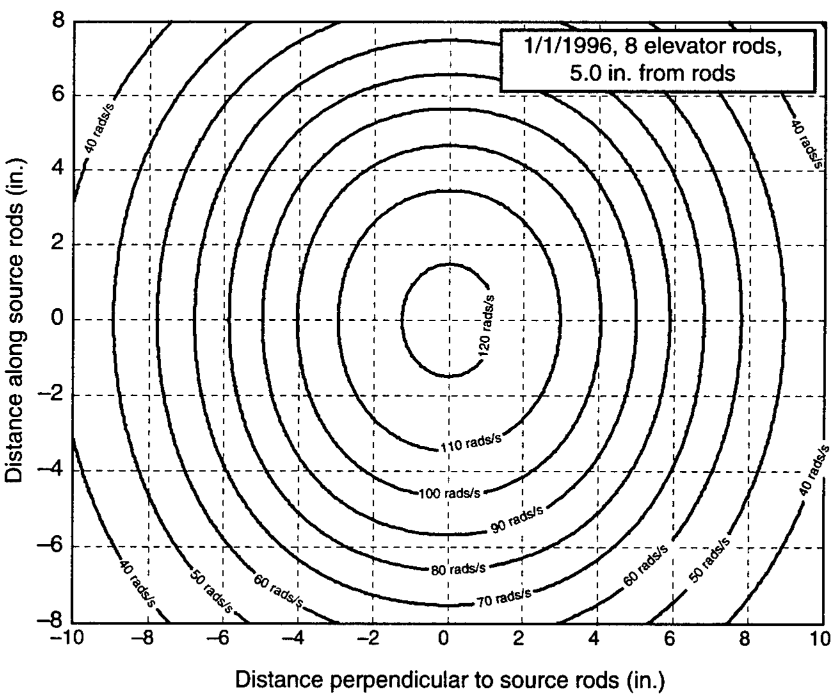

Figure 5. Sample result for a planar array of all eight high-intensity source rods, showing dose-rate contours in plane parallel to and 5 in. in front of rod plane.

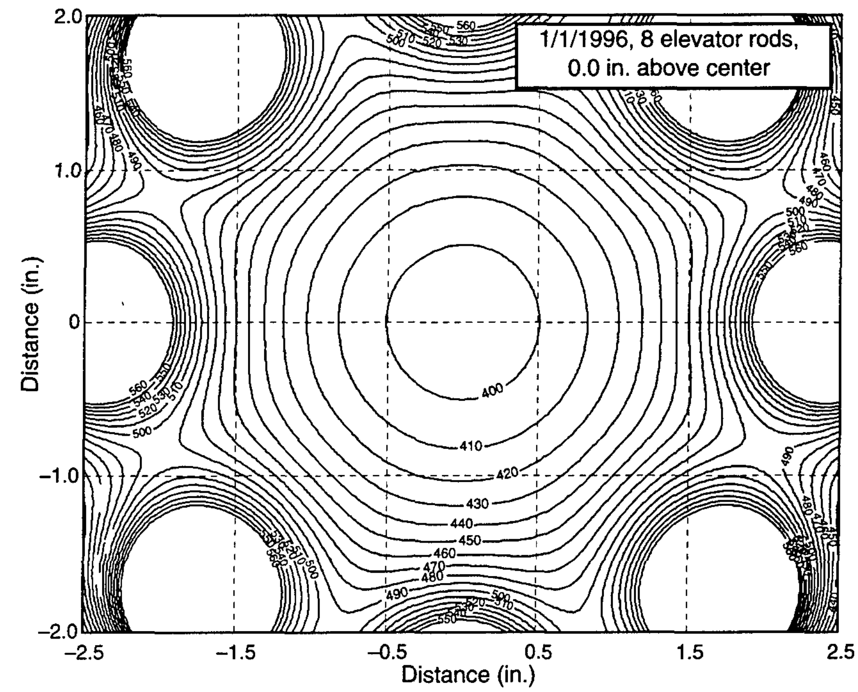

Figure 6. Sample result for a circular array of all eight high-intensity source rods, showing dose-rate contours in plane bisecting rods and parallel to floor.

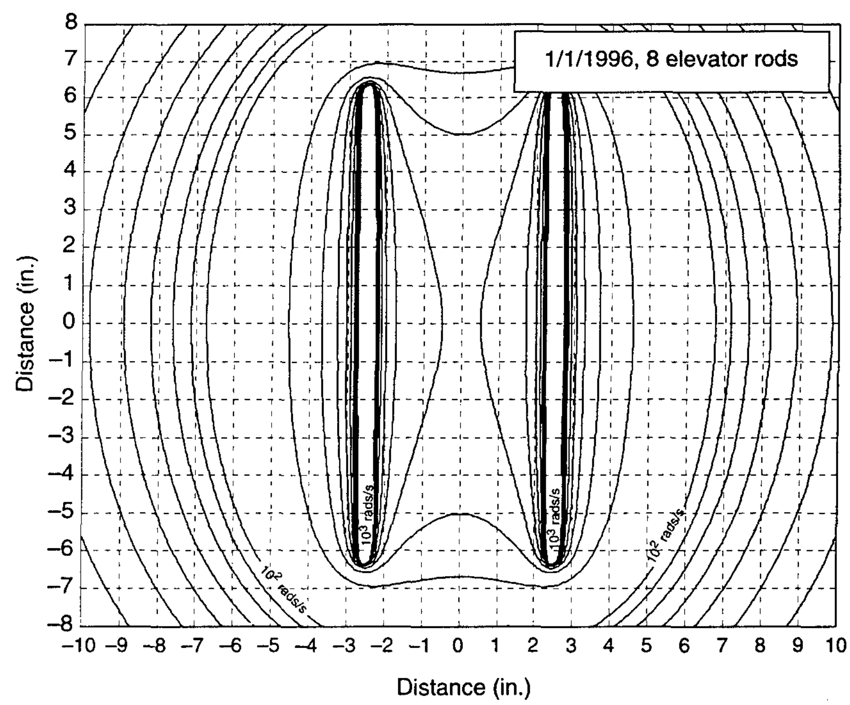

Figure 7. Sample result for a circular array of all eight high-intensity source rods, showing dose-rate contours in plane containing center line and first of eight rods.

7. Discussion of Approximations

The dose rates calculated inside the circular array are only approximate, since attenuation and scattering have been neglected. The attenuation factor $\exp -\frac{\mu}{\rho}\rho x$ (where x is the distance measured along the path through the material of density ρ) and the mass attenuation coefficient μ/ρ could have been added in equation (5); however, this leads to a form that is not integrable. I could have integrated equation (6) numerically; however, the improvement does not justify the effort at this time.

To some extent, scattering offsets attenuation. Photons originally headed somewhere else might undergo scattering and be redirected to the position of interest. This offset, known as buildup, can be dealt with either through Monte Carlo calculations or through empirical correction factors in the form $1+C\frac{\mu}{\rho}\rho x e^{D\frac{\mu}{\rho}\rho x}$. The buildup correction factor (along with attenuation) could be handled through numerical integration. Since the overall effect of buildup is to cancel a part of the attenuation, the small gain in accuracy does not justify the effort to include either attenuation or buildup.

In future upgrades to the program, I intend to describe the distribution of activity along the rods more accurately by dividing the helices into three sections. The end sections, which have a higher density of windings, will be given a proportionately higher activity per length than the center section.

Appendix. Cobalt-60

Cobalt-60 (symbolically ^{60}Co) is a radioactive isotope of the element cobalt, which is characterized by 27 protons in its nucleus. Besides the protons, the nucleus has a similar number of neutrons. The specific isotope ^{60}Co has 33 neutrons, for a total of 60 nucleons. The neutrons (which have no electric charge) provide the additional nuclear binding force needed to offset the mutual electric repulsion of the protons. Having too many neutrons, however, is also unstable. In particular, 33 neutrons are too many for the 27 protons in ^{60}Co. Given enough time, one of those neutrons will decay into a proton, an electron, and an anti-neutrino. The anti-neutrino need not concern us. It is massless, has no charge, and has such a small probability of interacting with anything that most pass through the entire earth. The electron or beta-minus (symbolically β^-), being electrically charged, interacts strongly with atomic charges and stops within a short distance of travel through objects such as metal. The proton and the rest of what had been a ^{60}Co nucleus constitute a new nucleus, nickel-60 (^{60}Ni), in an excited state that, being heavy, remains more or less in place. (The element nickel is characterized by 28 protons.) The excess energy in the ^{60}Ni nucleus is released in a very small fraction of a second in the form of γ radiation, which designates the electromagnetic radiation that originates within a nucleus. The γ radiation from the de-excitation of ^{60}Ni is the useful radiation from a ^{60}Co source.

Gamma radiation can be pictured as a large number of very small projectiles, called *photons*, travelling independently at the speed of light. Scattered radiation arises as the photons from the source pass through matter and interact with the subatomic particles (mostly electrons) of which matter is made up. The result is much like one billiard ball hitting another. With high-energy gamma radiation, such as from excited ^{60}Ni, the probability for an interaction is low. Therefore, to a reasonable degree of accuracy we can assume that the γ radiation makes it out of the stainless-steel containers and penetrates some distance through the water. However, in their travels, some of the photons collide like billiard balls with electrons in the water. This puts the electrons into motion at speeds that can exceed that of visible light in water. The result is the blue glow around the ^{60}Co, known as Čerenkov radiation.

The fundamentals of the statistical ^{60}Co decay process are described by quantum mechanics. Given two ^{60}Co nuclei, you cannot tell which will decay first. However, given sufficient nuclei, statistics pretty much guarantee that half the nuclei will decay into ^{60}Ni within the half-life. Half the remaining nuclei will then decay within another half-life, etc.

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A computer program is available for calculating dose-rate distributions for a variety of source configurations commonly used at the Army Research Laboratory Cobalt-60 Facility at Adelphi, MD. The underlying physics and mathematics are presented to document the program and to provide the necessary background for technicians serving as facility operators and other potential users of the program. Instructions for using the program are included.

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